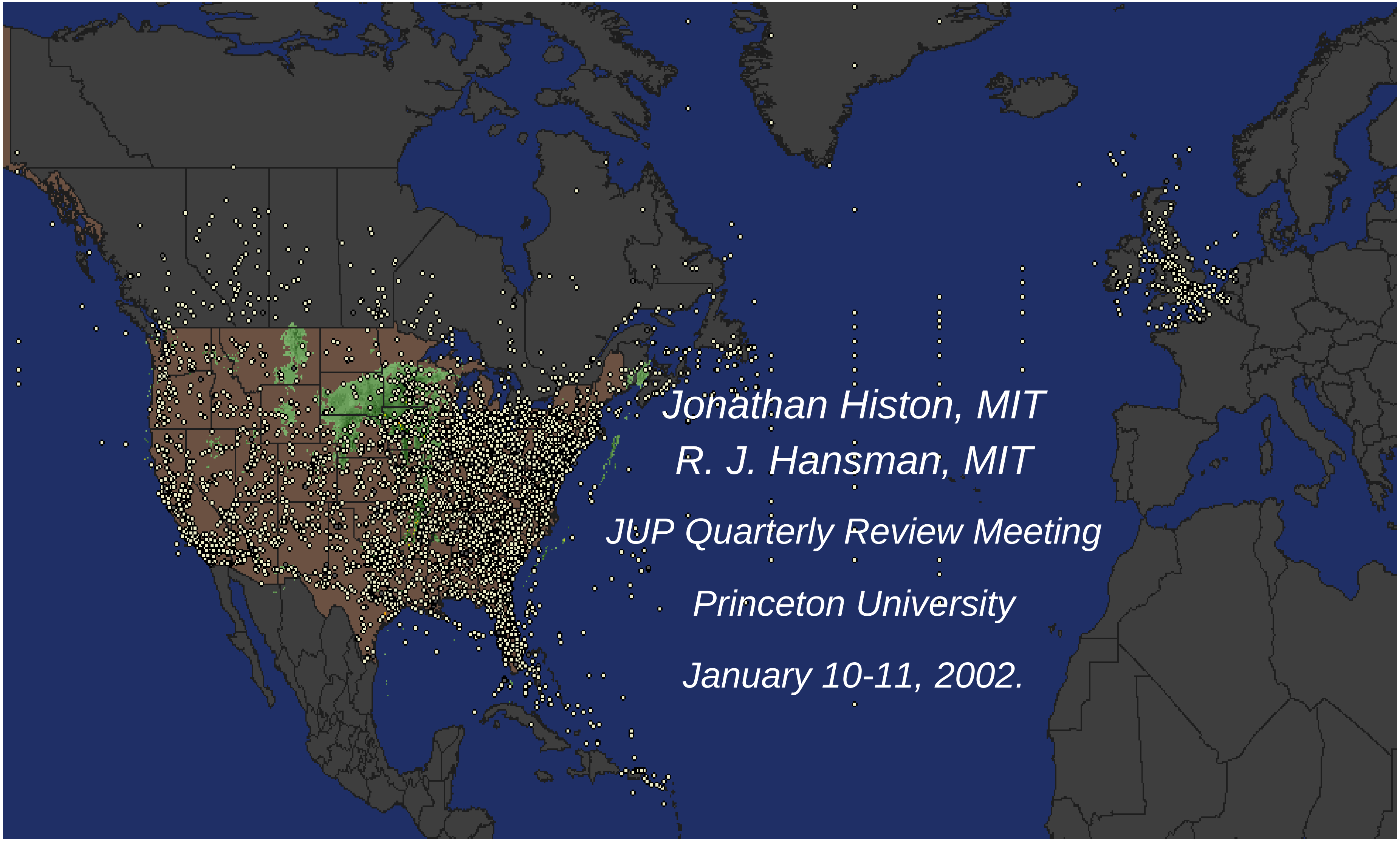
Introducing Structural Considerations Into Complexity Metrics



Jonathan Histon, MIT

R. J. Hansman, MIT

JUP Quarterly Review Meeting

Princeton University

January 10-11, 2002.

Hypotheses

- **Cognitive complexity is a limiting factor in ATC operations.**
  - Limits Acceptable Level of Traffic (ALOT) due to safety concerns.
  - Represents limiting factor in sector and system capacity.
- **Underlying structure is an important factor in cognitive complexity.**
  - Not considered in current metrics.
- **Improved understanding of how structure impacts cognitive complexity can be used to:**
  - Better define controller operational limits.
    - i.e. acceptable levels of traffic (e.g. Monitor Alert in ETMS)
  - Provide guidance for airspace and procedure design to reduce complexity.

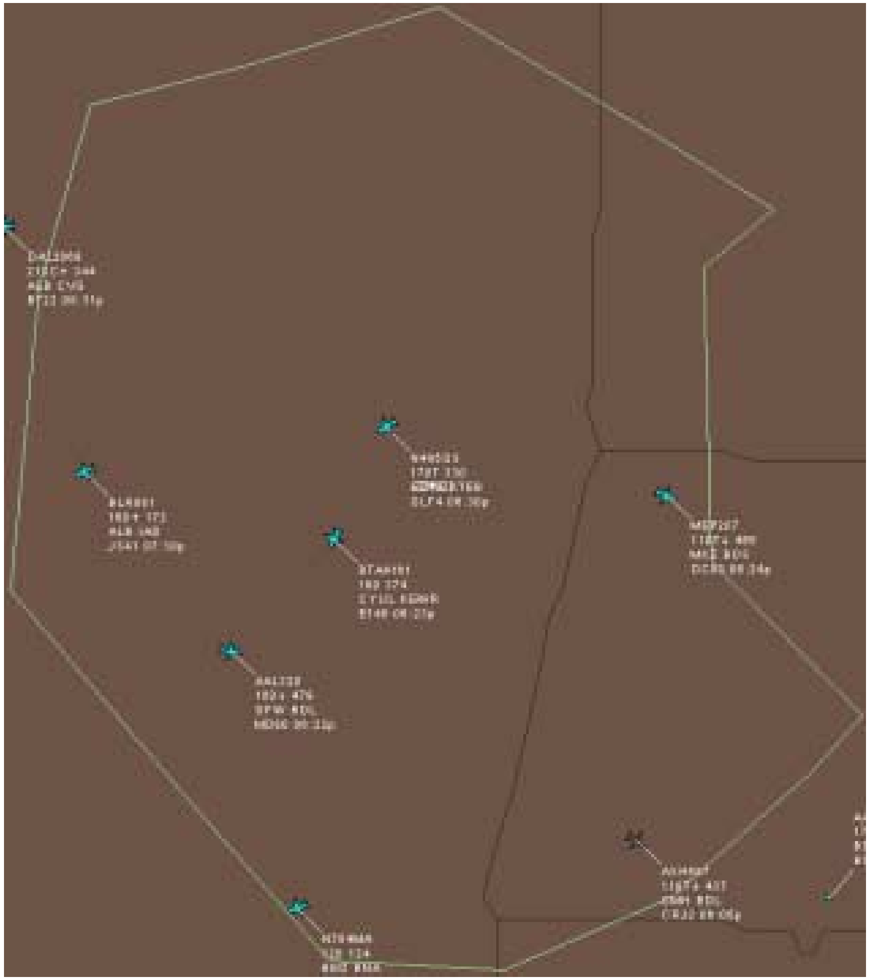
Structure Missing from Simple Instantaneous Complexity Metrics

Albany Sector, ZBW, 14:00:00 EST, November 30, 2001

- **Controllers mental representation richer than instantaneous observables on radar display.**

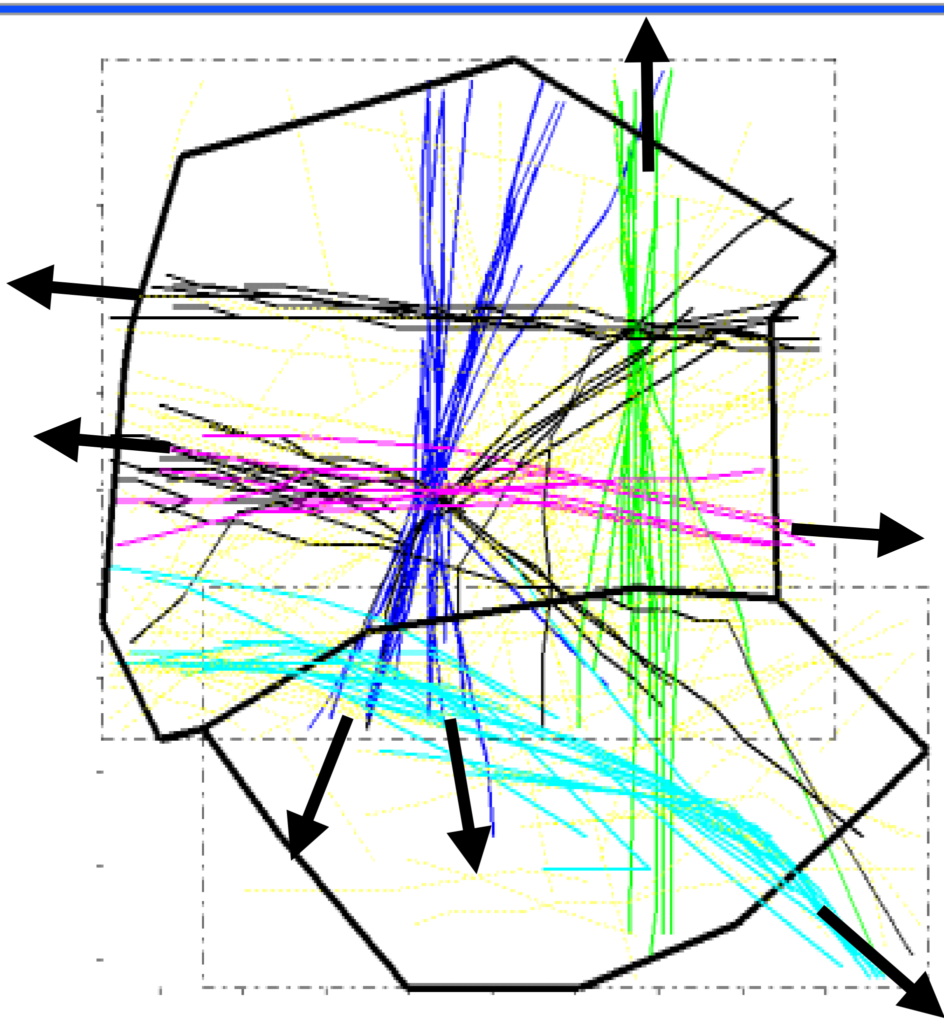
- **Most previous complexity metrics are geometric and based on observable states:**
  - ☐ Aircraft Densities
  - ☐ Number of Aircraft Transitioning
  - ☐ Points of Closest Approach

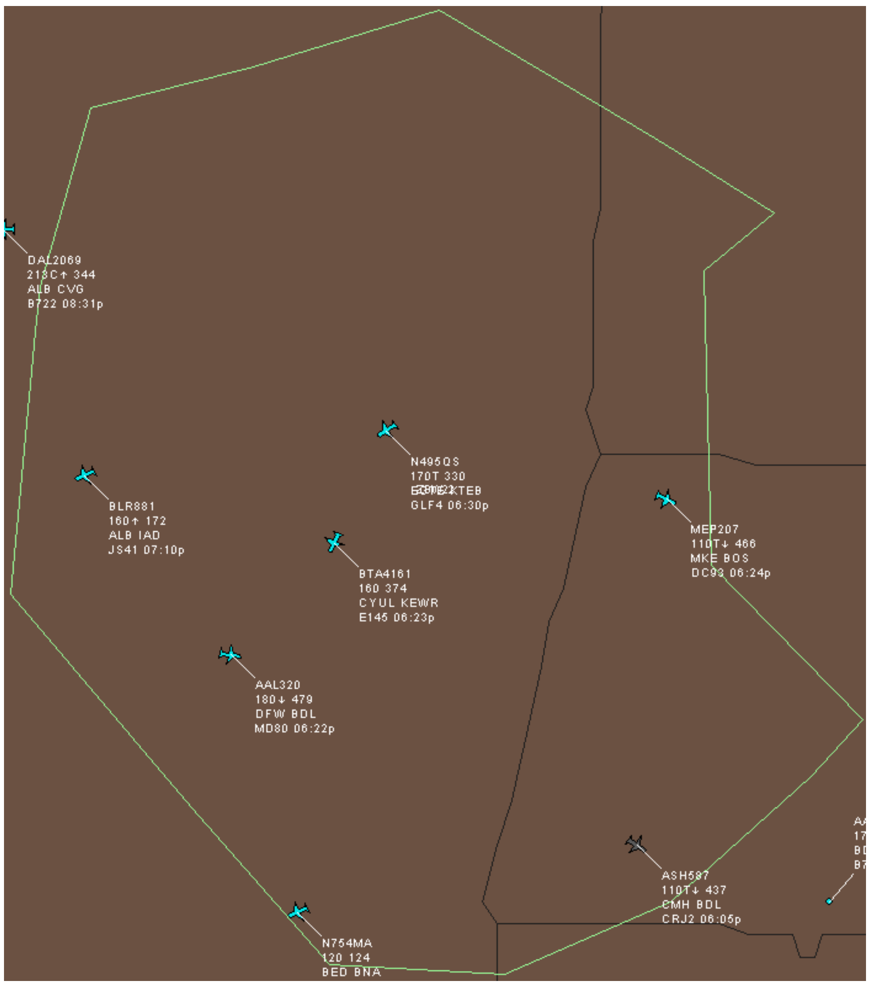
- ***But metrics fail to capture underlying structure…***



Example of Underlying Structure

ZBW, Albany Low Altitude Sector (110 – FL230), October 19, 2001





No metrics have been found that systematically include the impact of underlying structure on complexity.

Outline

- Show ETMS data supporting key complexity factors reported by controllers.
- Present model and examples of structure-based abstractions that appear to reduce cognitive complexity.
- Present preliminary formulation of explicitly including structural factors in a complexity metric.

Approach

- **Collaborative effort between MIT and Centre d'Etudes de la Navigation Aérienne (CENA).**
- **Observations to Identify Structural Factors Influencing Cognitive Complexity (MIT / CENA)**
  - Field Observations
  - Analysis of Standard Operating Procedures
  - Focused Interviews with Controllers
  - ETMS Data Analysis
  - Support Vector Machines
- **Preliminary Models of How Structure Influences Cognitive Complexity (MIT)**
  - Based on key structural factors.
  - Separates impact of structure on both controller inputs and outputs.
  - Focus on effect of structure on situational awareness on input side.
- **Preliminary Measures Including Structural Considerations (CENA / MIT)**
  - Explicit inclusion of identified structural factors.
  - Cluster-based approach.
  - Kolmogorov entropy.

Field Observations

- **Data Sources**
  - Focused interviews with controllers, TMU, training department personnel.
    - What are the key factors driving complexity?
    - What is the most / least difficult sector?
    - What airspace changes would you make to reduce complexity?
  - Documented Standard Operating Procedures
  - Observed controllers during live operations.
- **Facilities visited:**
  - En-route (Centers)
    - Boston, Cleveland, Montreal, Bordeaux
  - Terminal area (TRACON / TMA)
    - Boston

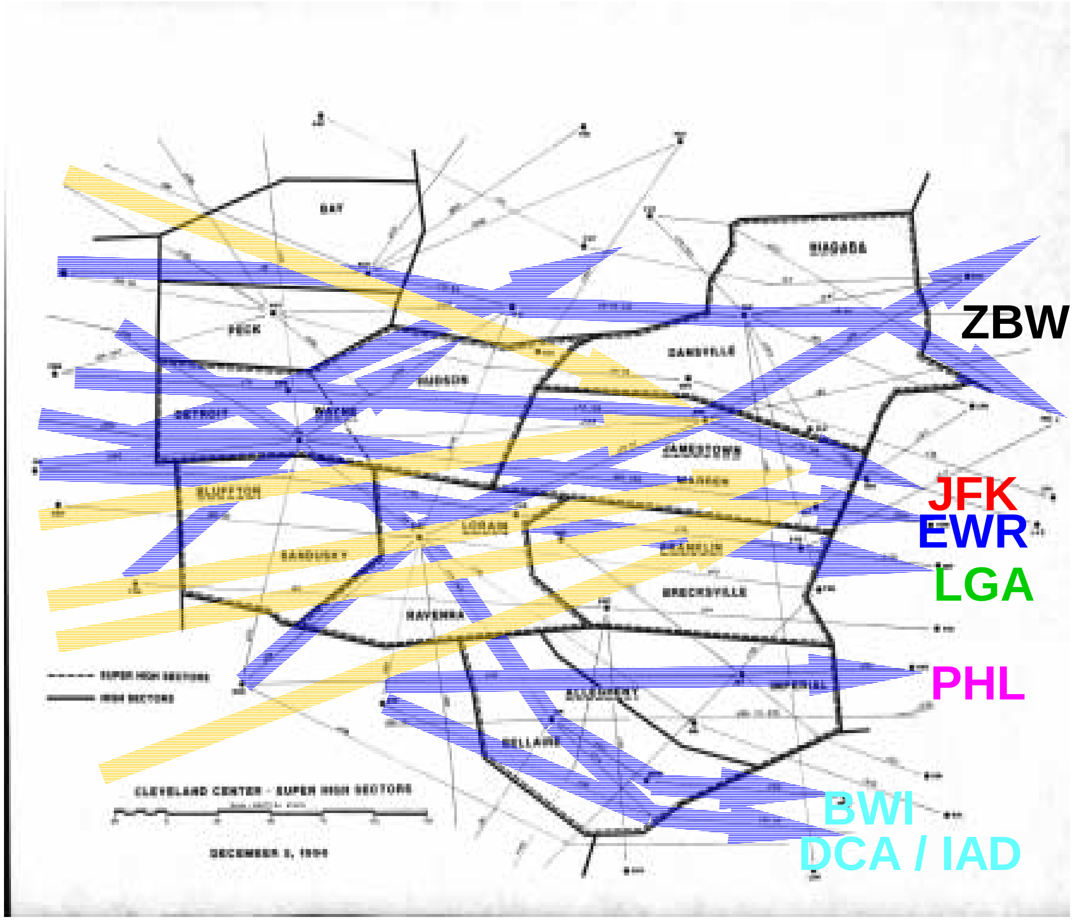
Focused Interviews Results:

“What are the key factors driving complexity?”

- **Airspace Factors**
  - Sector dimensions
  - Spatial distribution of airways / Navigational aids
  - Coordination with other controllers
  - Number and position of standard ingress / egress points
  - Standard flows
- **Traffic Factors**
  - Density of aircraft
  - Aircraft encounters
  - Ranges of aircraft performance
  - Number of aircraft in transition
  - Sector transit time
- **Operational Constraints**
  - Buffering capacity
  - Restrictions on available airspace
  - Procedural restrictions
  - Communication limitations

Airspace Factors

- **Sector dimensions**
  - ☐ Shape
  - ☐ Physical size
  - ☐ Effective “Area of regard”
- **Spatial distribution of airways / Navigational aids**
- **Coordination with other controllers**
  - ☐ Point-outs
  - ☐ Hand-offs
- **Number and position of standard ingress / egress points**
- **Standard flows**
  - ☐ Number of
  - ☐ Orientation relative to sector shape
  - ☐ Trajectory complexity
  - ☐ Interactions between flows (crossing points, merges)



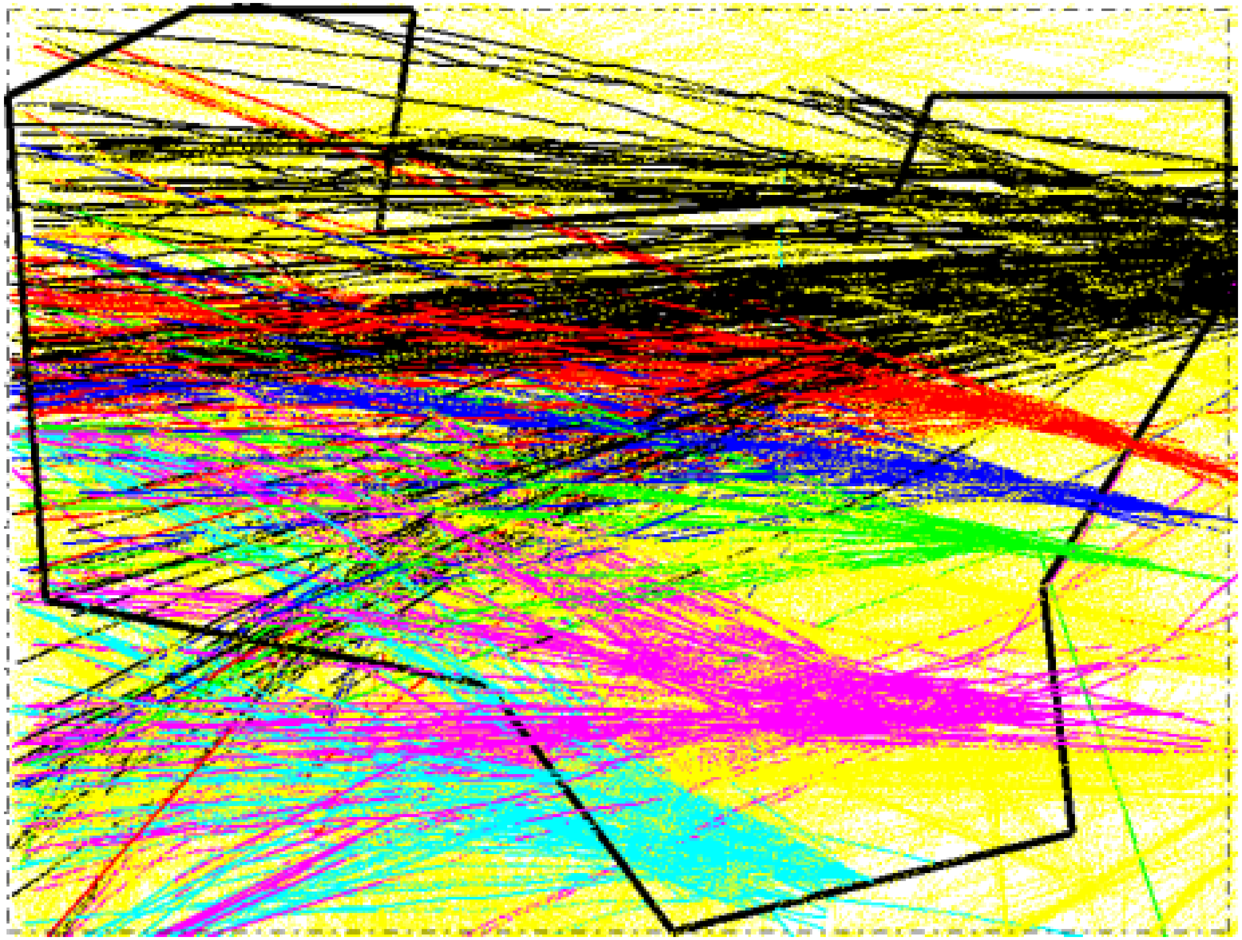
EAST FLOWS **NRP ROUTES**

Graphics courtesy of Tom Roherty, TMU, ZOB.

Standard Flows, ZOB

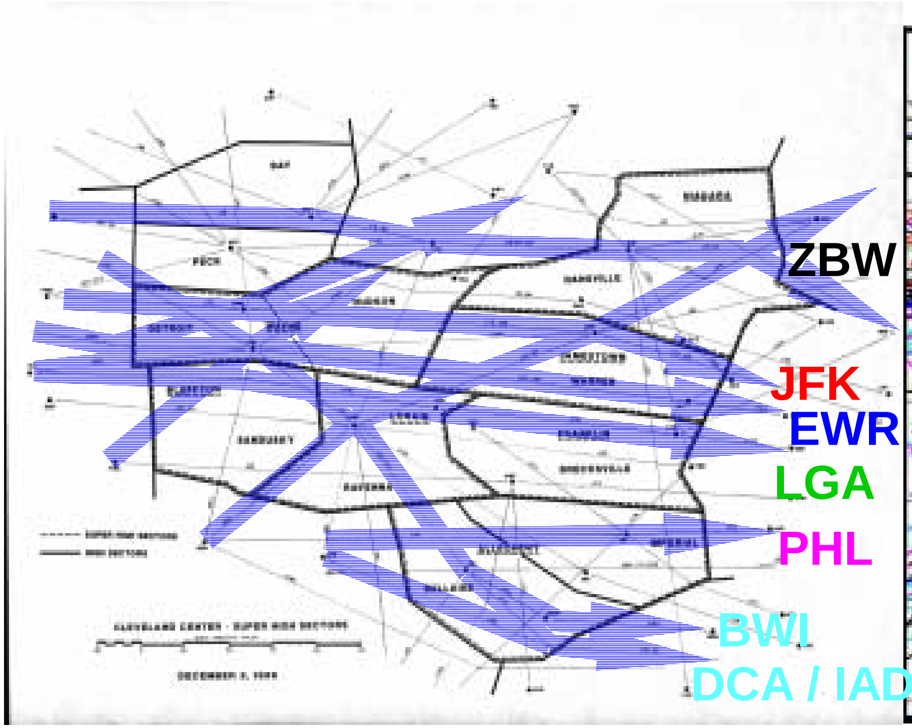
October 19, 2001, 24 hours

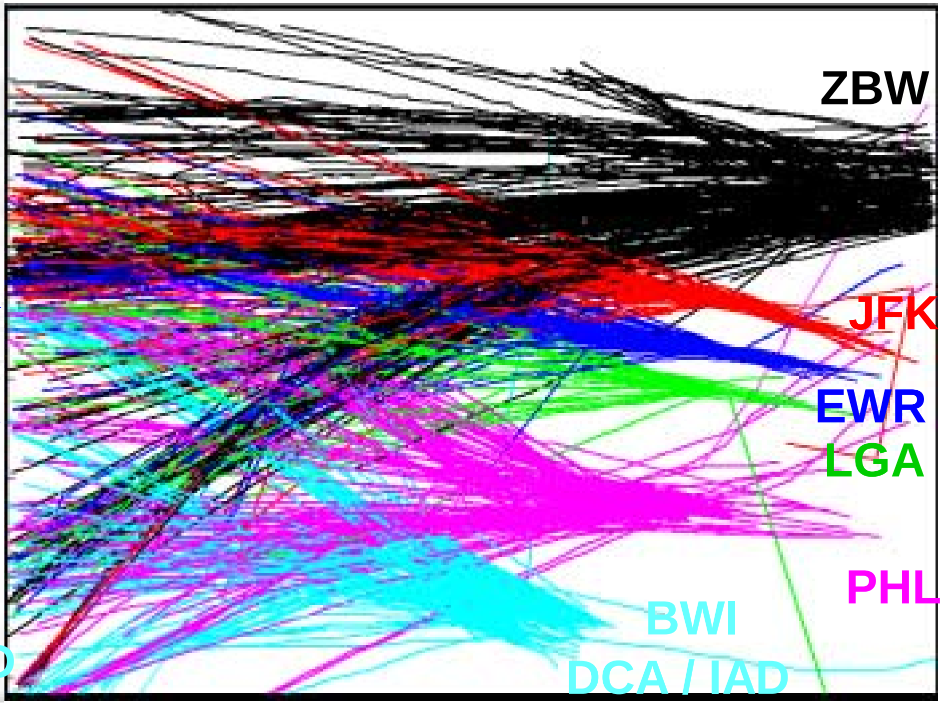
- **4497 Aircraft**
- **Colored by nominal flow destination:**
  - ☐ **ZBW (Boston Center)**
  - ☐ **JFK**
  - ☐ **EWR**
  - ☐ **LGA**
  - ☐ **PHL**
  - ☐ **BWI / DCA / IAD**
  - ☐ **ALL OTHER AIRCRAFT**



Standard Flows, ZOB
October 19, 2001, 24 hours

- **Can easily identify distinct Eastbound flows in lateral dimension:**



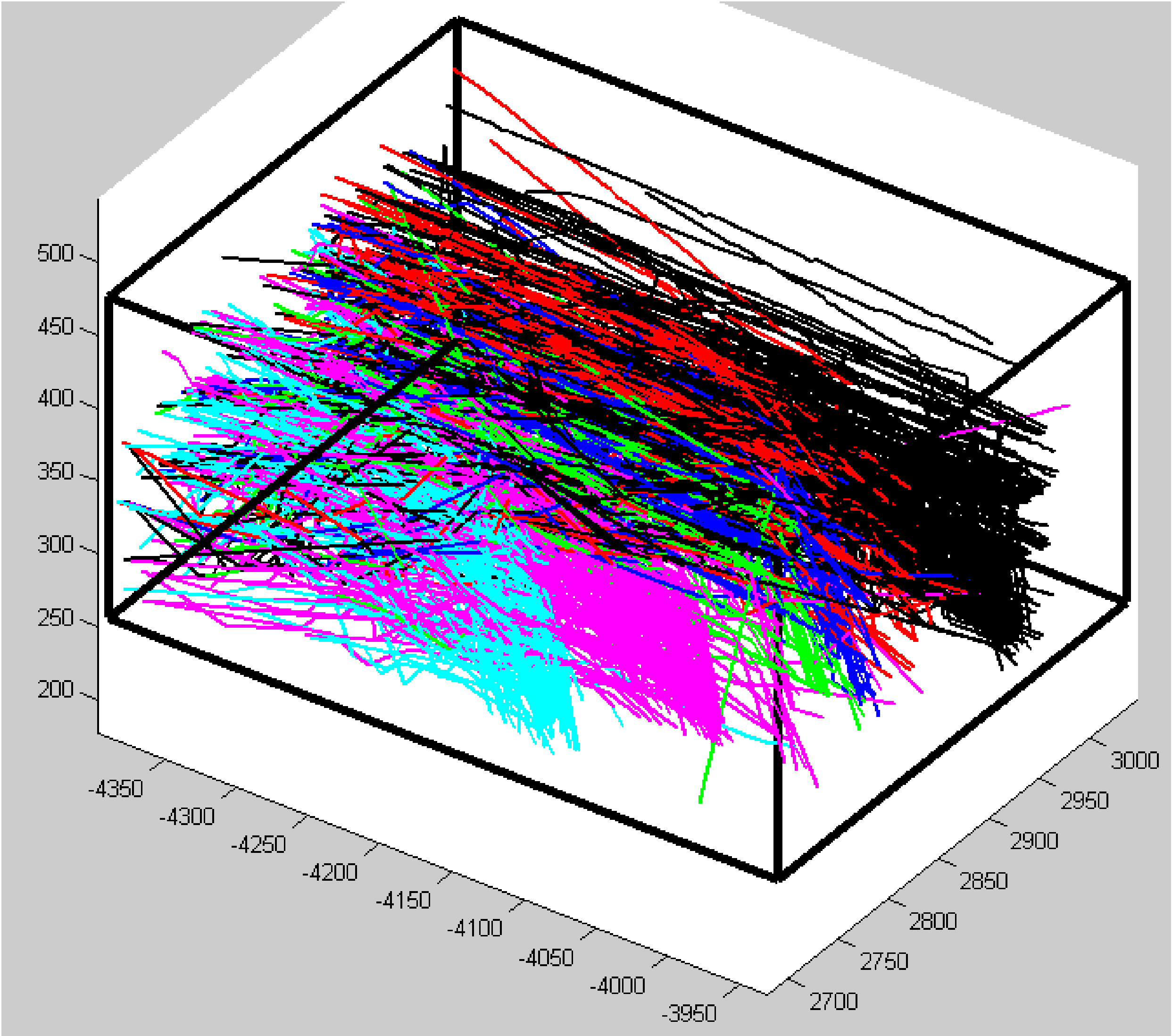


Left graphic courtesy of Tom Roherty, TMU, ZOB.

Standard Flows, ZOB

October 19, 2001, 24 hours

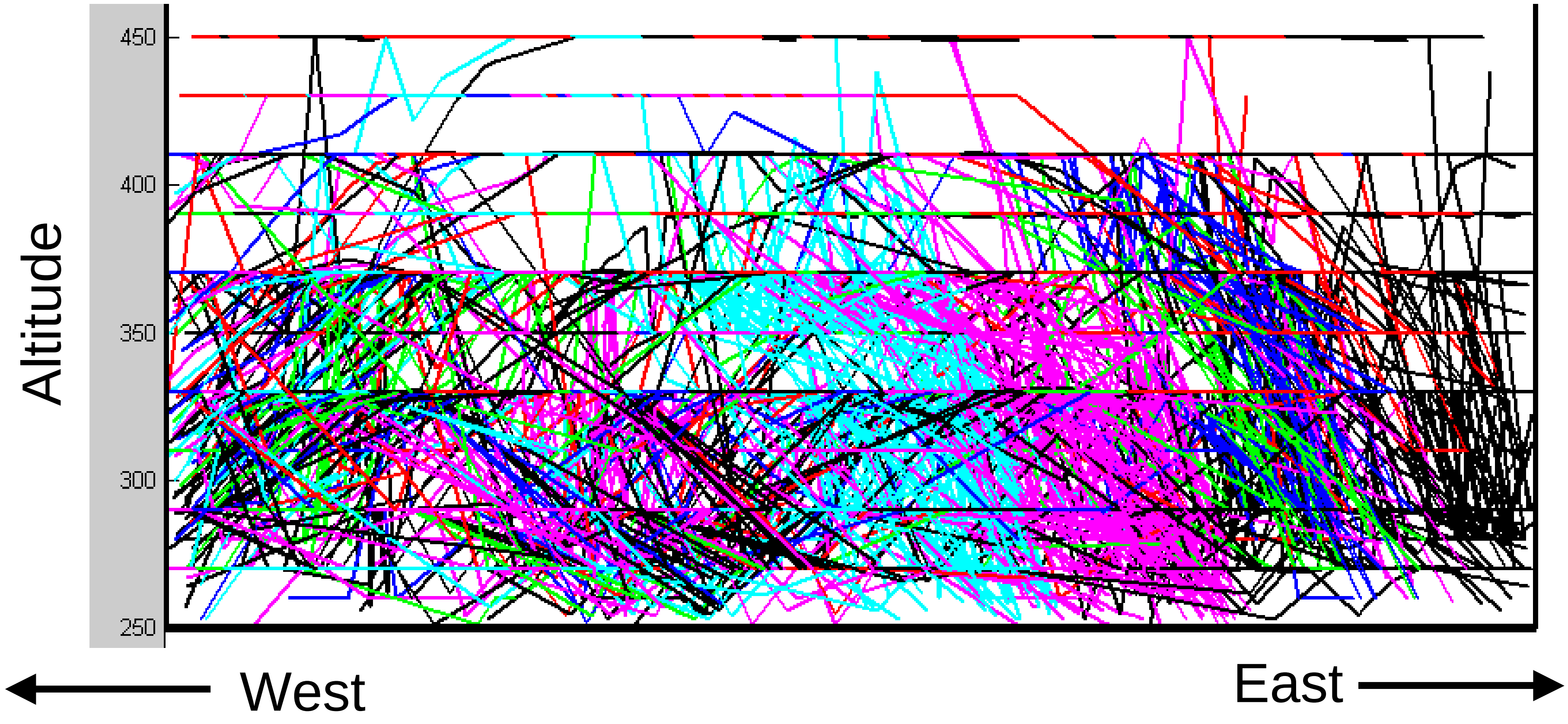
- **Perspective View**



Standard Flows, ZOB

October 19, 2001, 24 hours

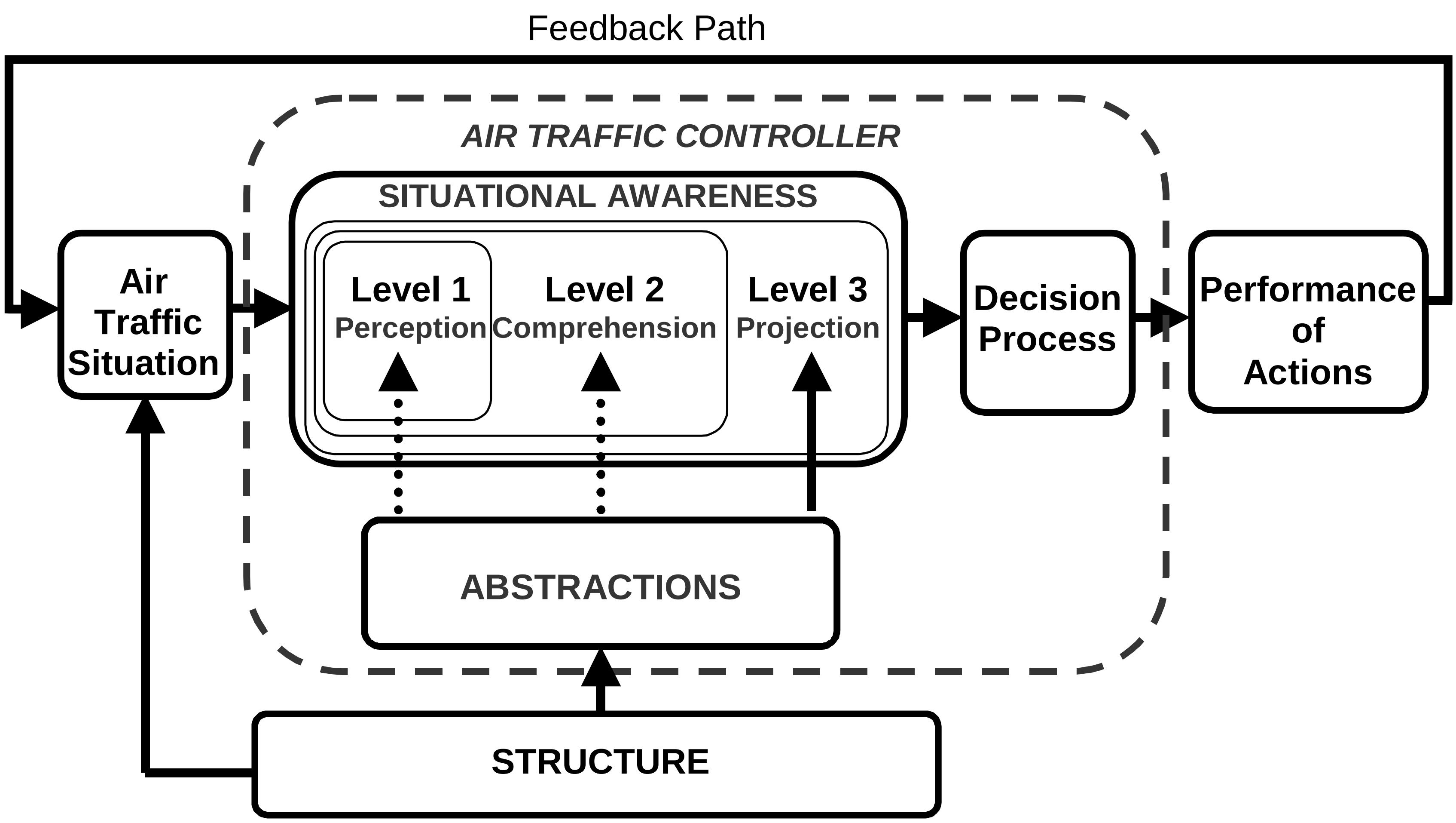
- **Flows exhibit greater variability in the vertical dimension:**



Complexity and Structure

- **Investigated mechanisms by which structural factors appear to reduce controller cognitive complexity based on simple controller task model.**
- **Key tasks of Air Traffic Controllers:**
  - Planning
  - Monitoring
  - Intervening
- **Structure appeared to be used as a basis for abstractions to reduce cognitive complexity.**
  - Situation Awareness Impact

Impact of Structure Based Abstractions on Situational Awareness

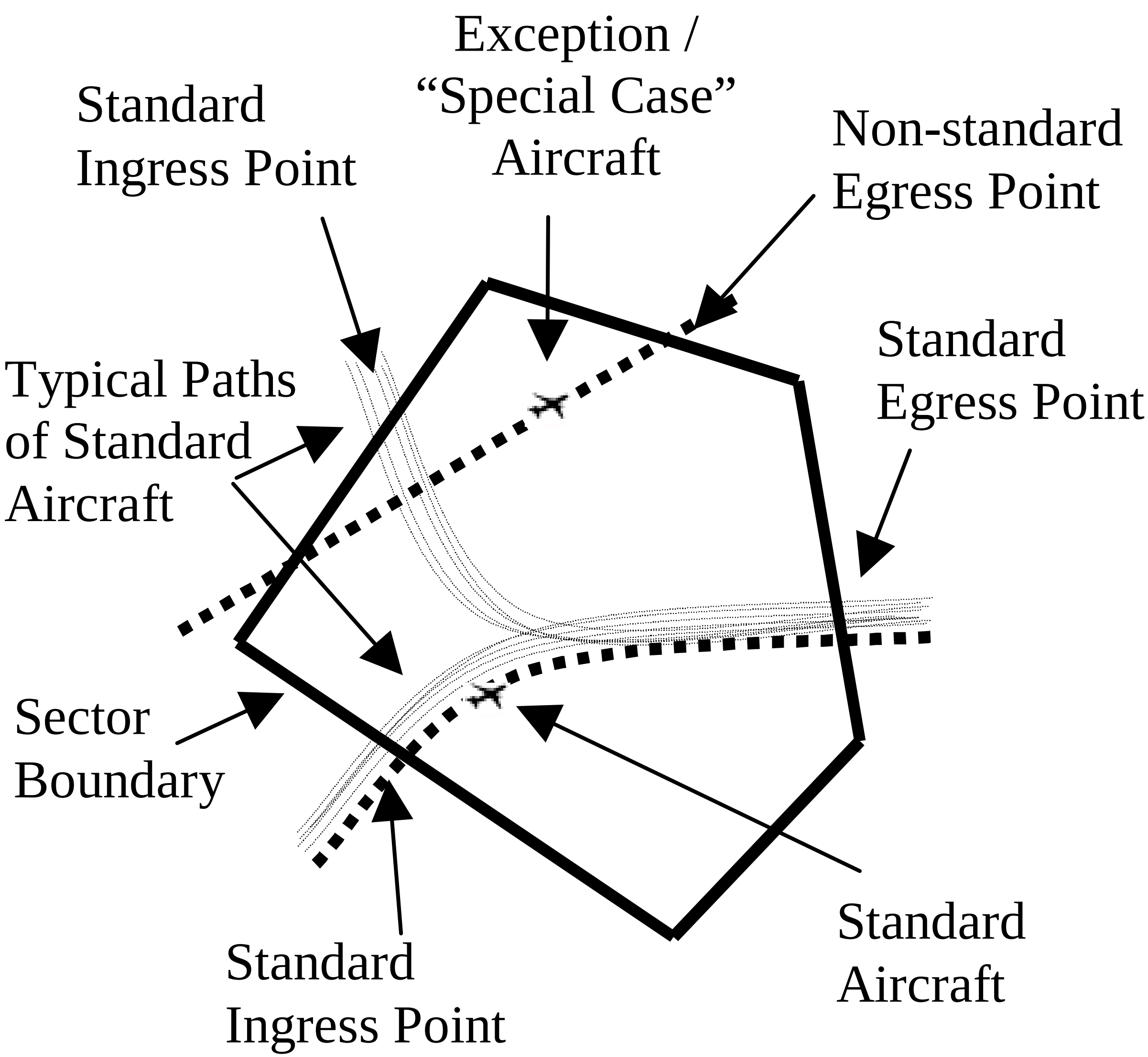


Based on Endsley Situation Awareness Model

Examples of Structure-Based Complexity Reduction Mechanisms

- **Standard Flows**
  - Provide generalized expectation of route through airspace
    - Planning difficulty reduced
    - Monitoring task simplified
    - Intervention
      - ↓ Reduced for standard flow aircraft
- **Groupings**
  - Shared properties can be used to segregate traffic situations
  - Creates distinct problems, reducing overall scale / dimension of problem:
    - Planning difficulty reduced
    - Monitoring task simplified
    - Intervention coordination costs reduced
- **Critical Points**
  - Create concentration of focus on spatially localized points:
  - Shifts planning and monitoring from spatial to temporal coordination
    - Planning difficulty reduced
    - Monitoring task focused

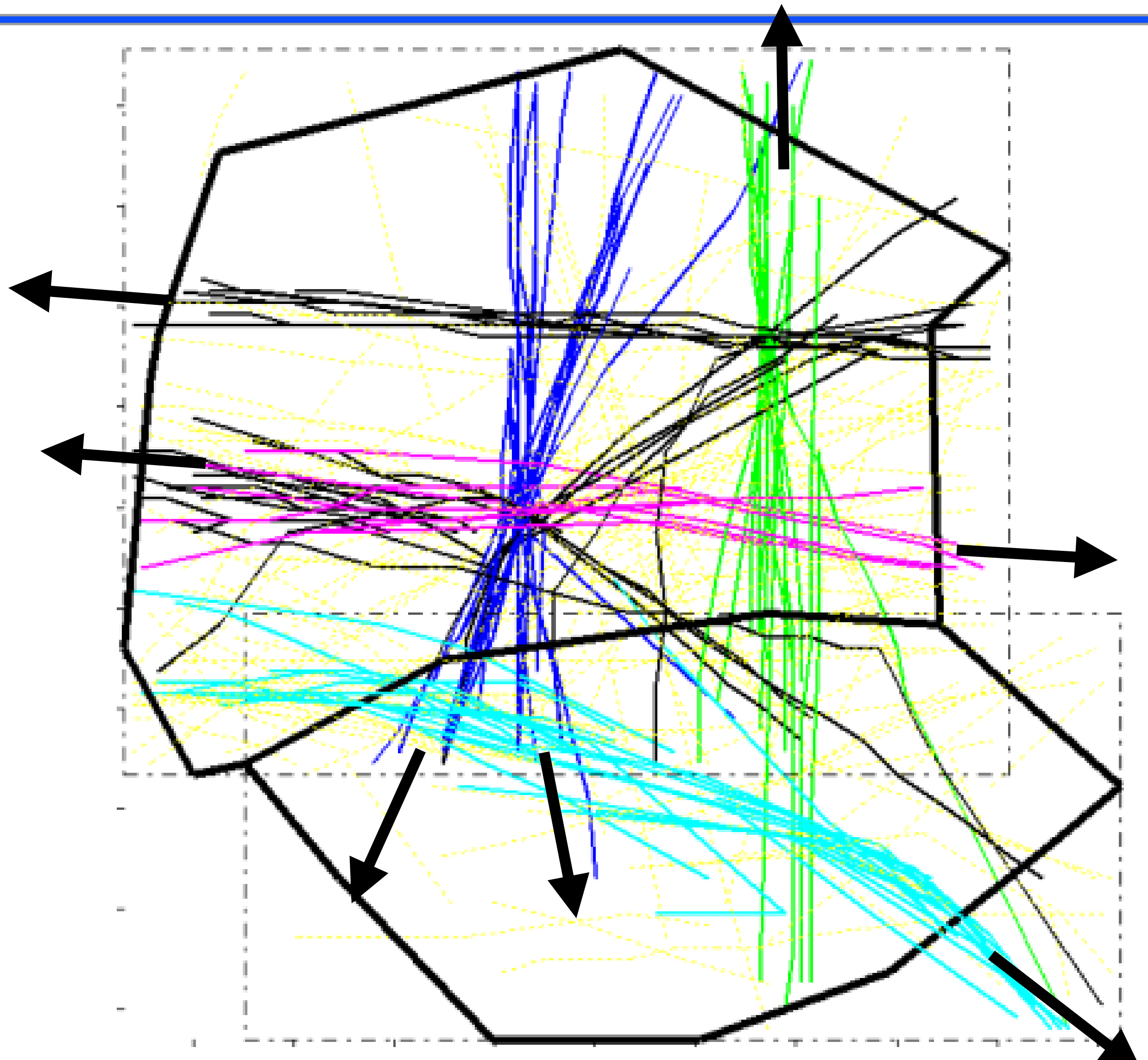
Standard Flow Abstraction



Standard Flow Abstraction Example

ZBW, Albany Low Altitude Sector (110 – FL230), October 19, 2001

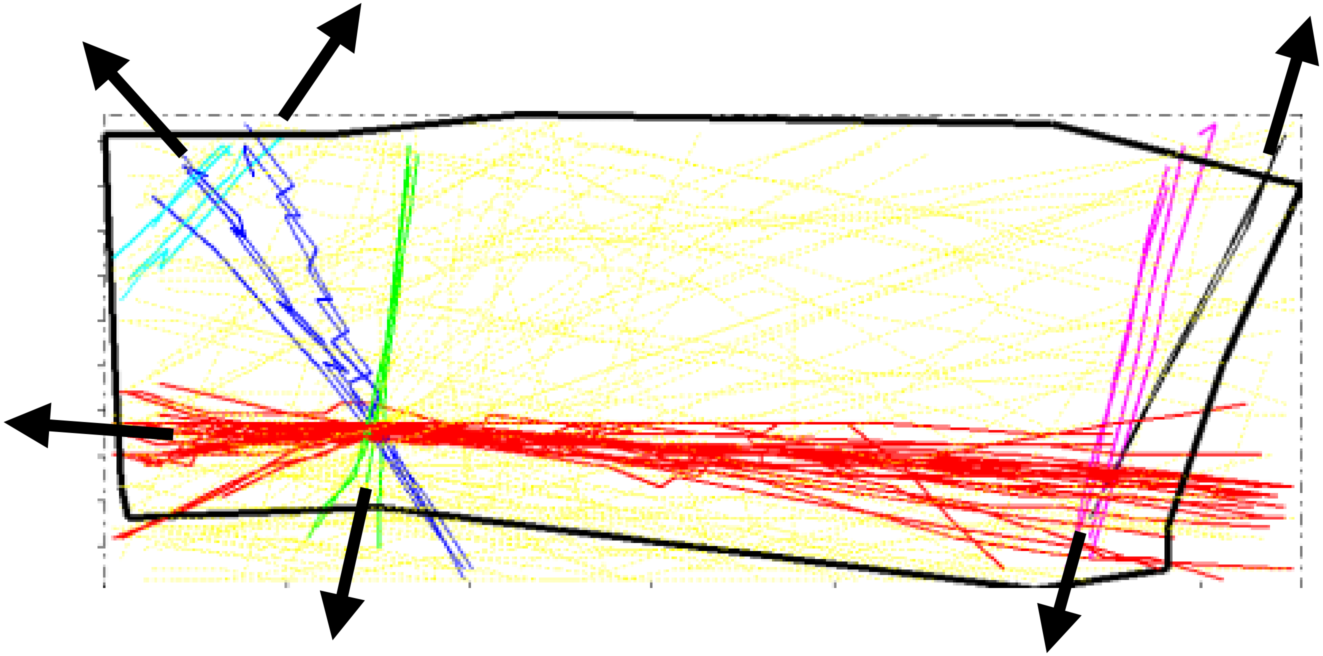
- **Identified as "Hard" Sector**
- **231 aircraft trajectories over 24 hours**
- **Flows shown capture 43% of all trajectories**



Standard Flow Abstraction Example

ZBW, Utica High Altitude Sector (FL180 – FL999), October 19, 2001

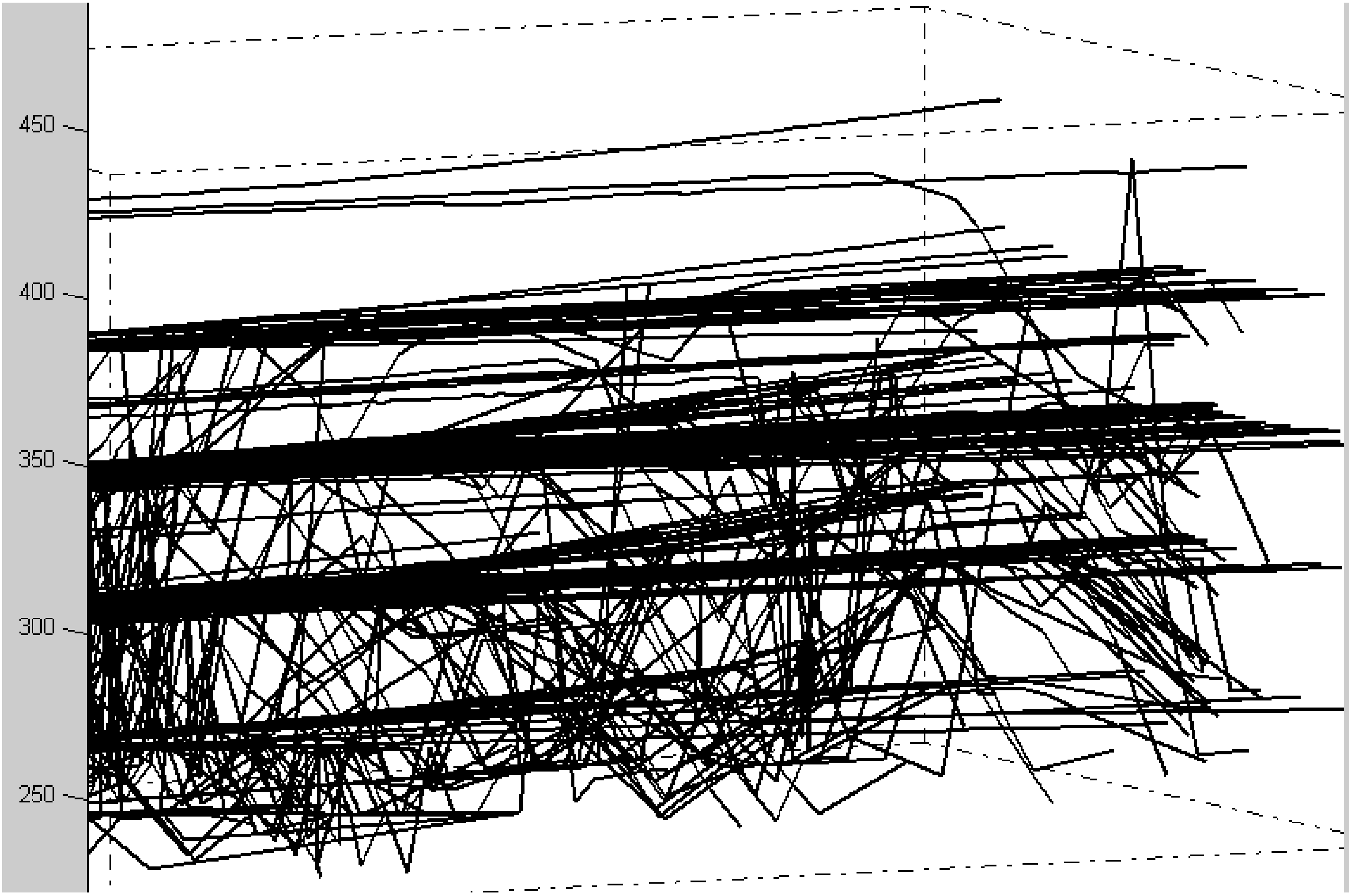
- **Identified as "Easy" Sector**
- **268 aircraft trajectories over 24 hours**
- **Flows shown capture 19.8% of all trajectories.**



Grouping Example

Standard Flight Levels

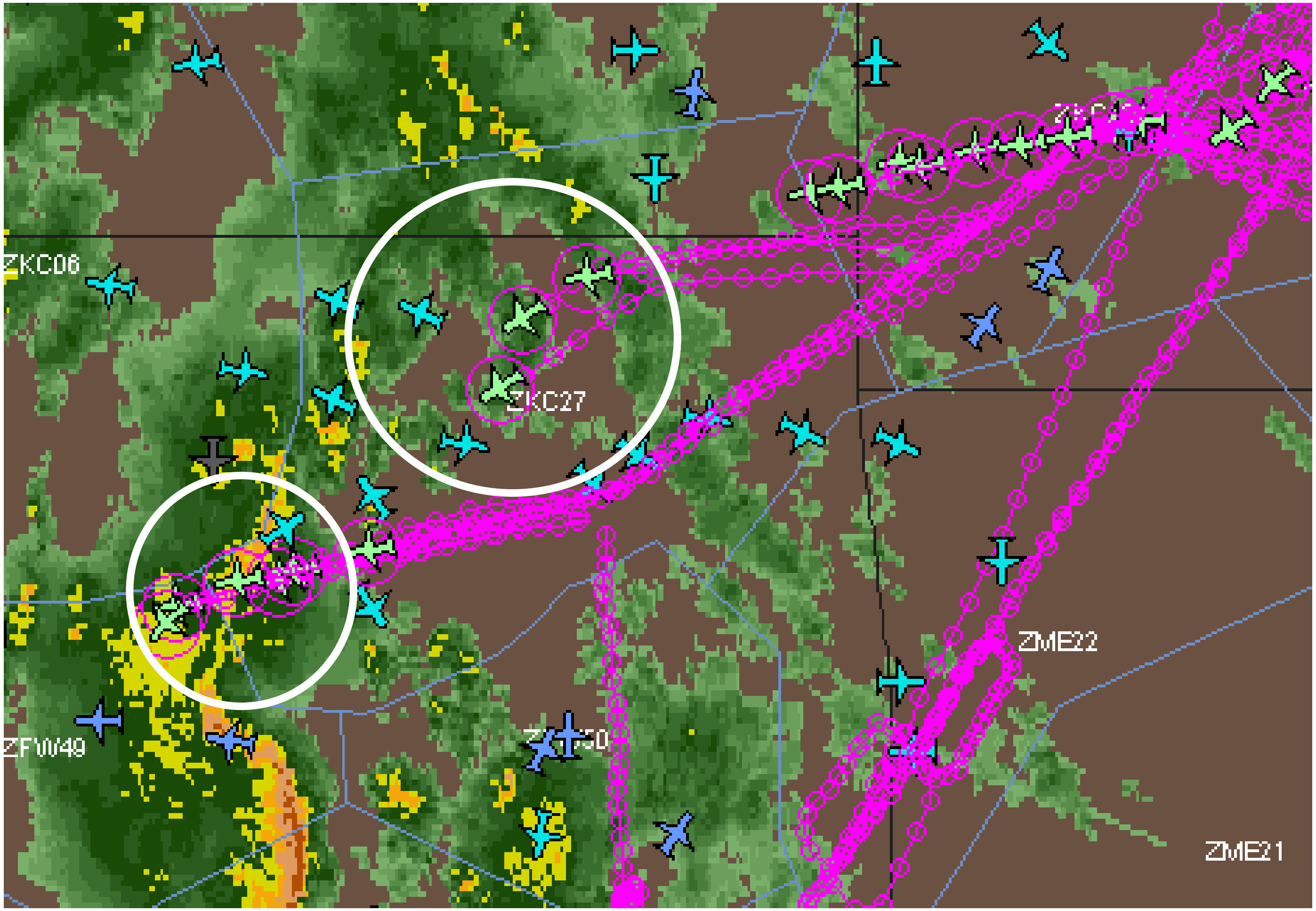
ZOB – ZBW Traffic



Grouping Example
Dallas Reroute

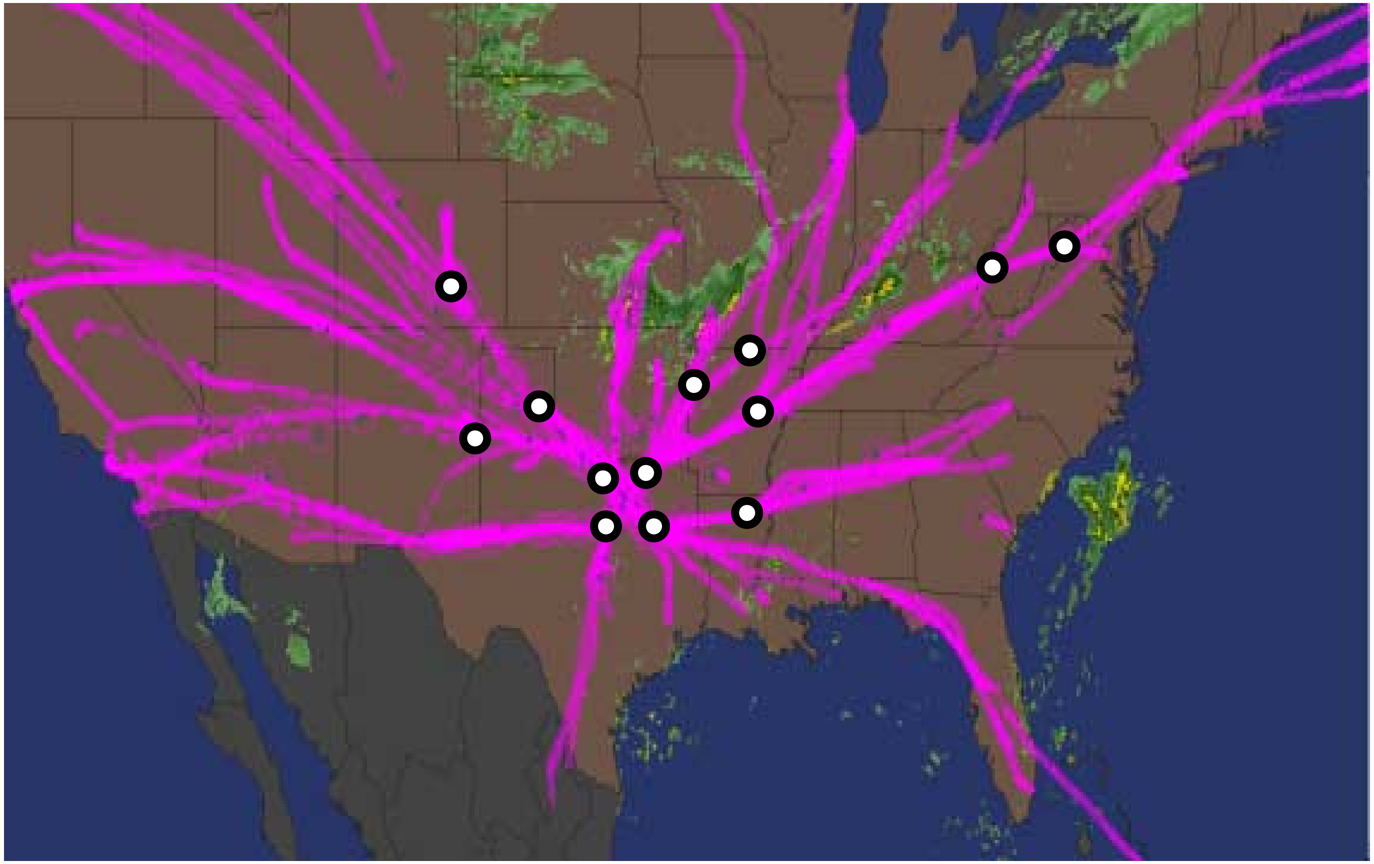
- **May 4, 2001 9:05 p.m.**

DFW
In-bound



Critical Points Example
Dallas Fort-Worth

- **Critical points arise in part from branching structure of arrival routes:**



- **June 20, 2001 12:19 p.m. 153 Aircraft In-bound**

Critical Points Example
Chicago Arrival Sectors

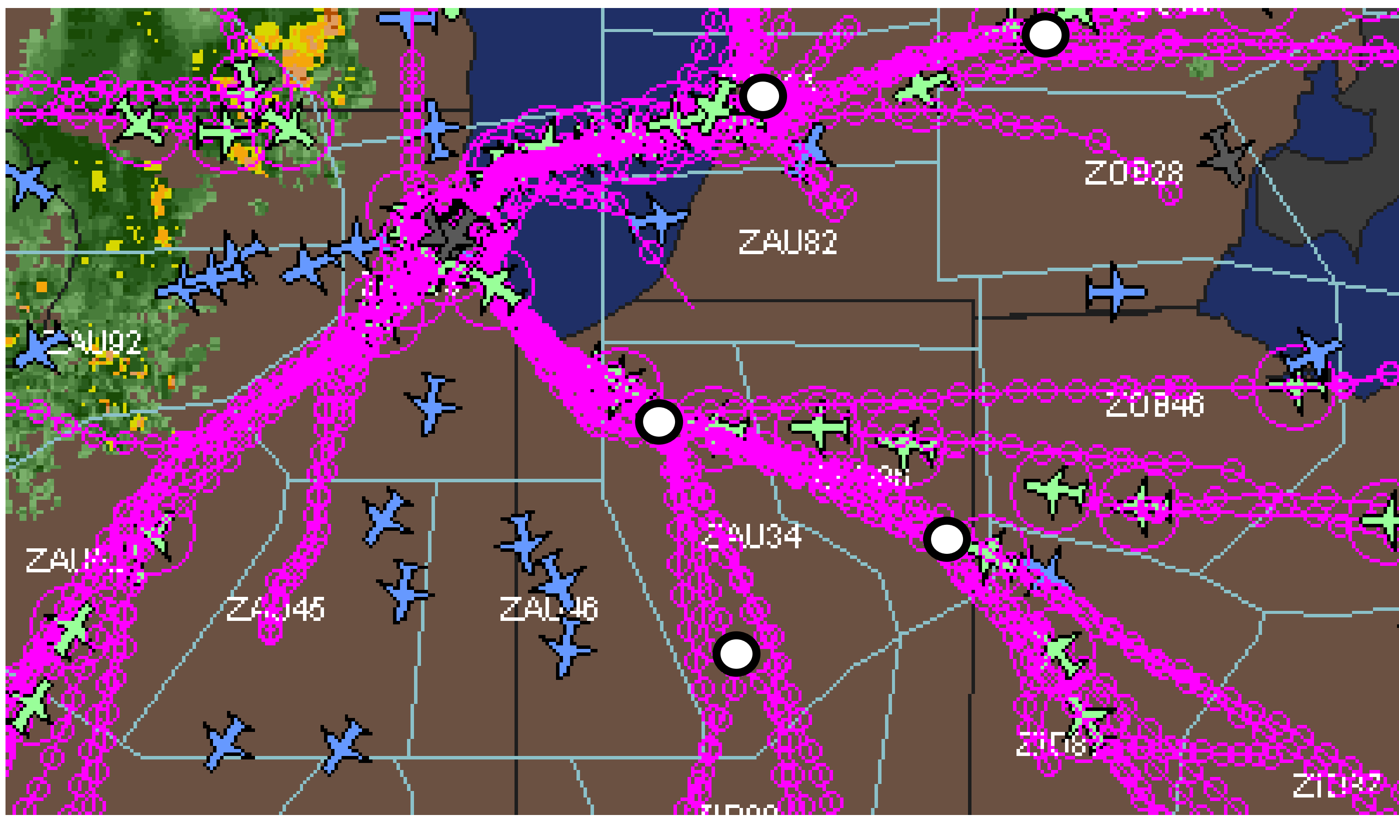
- **Example: Chicago, May 3, 8:59 p.m.**

Sector Boundaries

In-bound ORD

In-bound's Route Flown

Out-bound ORD

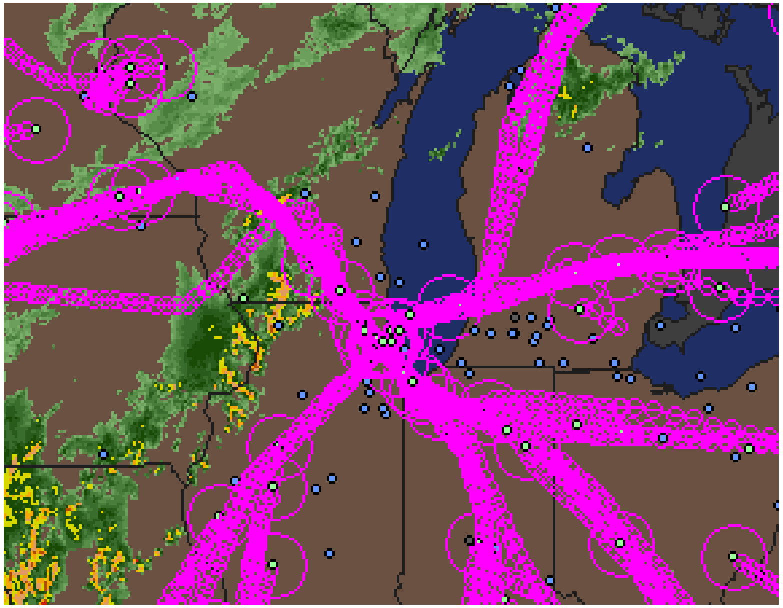


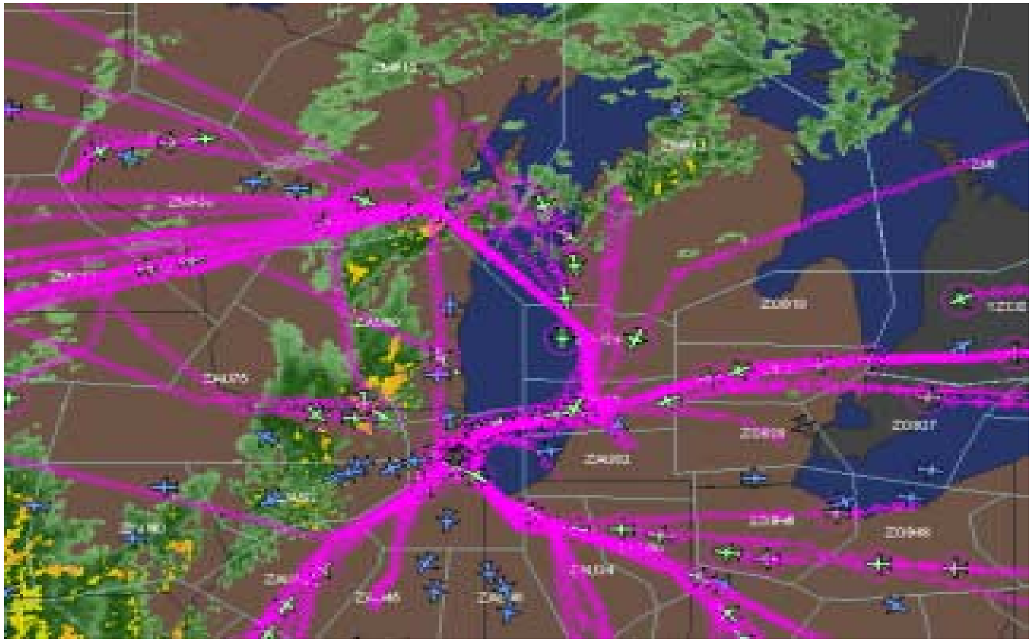
Robustness

- **Controllers must guarantee safe operation under normal *and* abnormal conditions.**
- **Structure-based abstractions can be dynamic:**
  - Will tolerate minor perturbations
- **Under non-nominal conditions, the underlying structure may no longer support the abstraction:**
  - I.e. convective weather blocking a route.

Robustness Example
Convective Weather in Chicago

- **Weather disrupting NW corner fix into Chicago perturbs standard flow abstraction.**





- **Two responses observed:**
  - ☐ Standard flow abstraction for aircraft traversing the weather no longer available – aircraft treated as “special cases.”
  - ☐ Alternative standard flow abstraction is used.

Explicit Inclusion Approach (Preliminary)

- **Create measure based on "Effective Number of Aircraft"**
  - Total Difficulty is referenced to difficulty of a "baseline" aircraft, $D_{Baseline}$

$$Total\ Difficulty = N_{Effective}\ D_{Baseline}$$

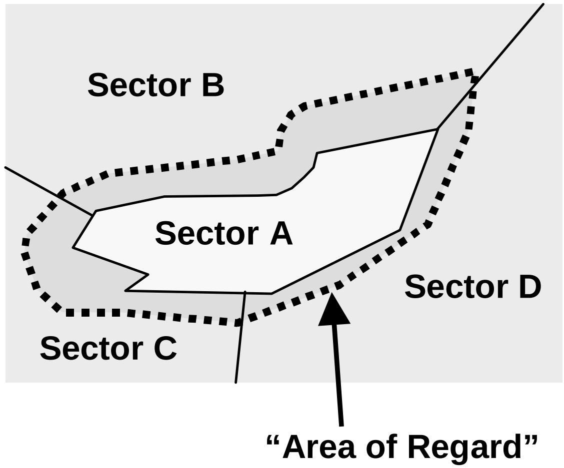
- **Difficulty Multiplier, DM_i, is relative difficulty of i^{th} aircraft:**

$$(DM)_i = \frac{Difficulty_i}{Baseline\ Difficulty}$$

- **$N_{Effective}$ computed from contribution of Difficulty Multiplier, DM_i, of each aircraft**

$$N_{Effective} = \sum_{i=1}^{M} (DM)_i \cdot (1)$$

M = Number of Aircraft in "Area of Regard"



Explicit Inclusion Approach

- **Difficulty Multiplier explicitly includes structural factors**

$(DM)_i$ = **f (*Standard Flow Membership (i)*)** $\times$
f (*Location Relative to Critical Points (i)*) $\times$
f (*Cluster / Grouping Membership (i)*) $\times$
f (*Encounters With Other Aircraft (i)*) $\times$
f (*Aircraft Performance (i)*) $\times$
f (*Coordination / Communication Load (i)*) $\times$
f (*Aircraft Transitioning Behavior (i)*) $\times$

...

...

Summary

- **Instantaneous traffic distributions do not capture complete story of complexity for air traffic controllers.**
- **Observations of ETMS data support capture key complexity factors reported by controllers.**
  - Flows through Cleveland Center
- **Present model and identify some key structure-based abstractions that reduce cognitive complexity**
  - Standard Flows
  - Groupings
  - Critical Points
- **Preliminary formulation of explicitly including structural factors in a complexity metric.**
  - Represented by Effective Number of Aircraft
  - Approach based on Difficulty Multipliers